

EQUILIBRIUM CONDENSATION IN A SOLAR NEBULA

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In attempts to reconstruct the environment of condensation of solar system materials, particularly exemplified by certain meteorite components, the relative temperatures of the gas and the solid are of critical importance. The relationships that determine the heat balance in a circumsolar grain-gas system are examined. Fundamental considerations show that regardless of opacity or gas density, the gas will always be at a higher temperature than the solid in such regions of the system where condensation is possible. Implications of the characteristic temperature differential between the gas and the condensing solid are discussed.

INTRODUCTION

One of the primary objectives of meteorite research is to draw inferences about the early states of the solar system. Such inferences derived from chemical analysis are relied upon by astrophysicists as hard evidence for the primordial conditions in the circumsolar region. Physical arguments about the configuration and state of matter are in their turn used as a basis for assumptions in interpreting the chemical data.

Much of the recent interpretation of the phase chemistry of meteorites has been based on the arbitrary postulate that the temperatures of the gas and of the solid grains growing from it at condensation were identical or similar. It is generally assumed that the condensing system consisted of a rotating disc of hot neutral gas. Cooling, presumably achieved by radiation, led to condensation and growth of grains with temperatures identical to those of the gas, and with structure and composition determined by this temperature equilibrium.

Fundamental consideration of the energy exchange in gases and solids shows that it is impossible for solid grains in space to remain at the same temperature as the gas if the gas temperature differs from that of the radiation field. Under the conditions visualized in the models mentioned, the temperature differentials between the gas and the major solids would amount to at least several hundred degrees. This conclusion is insensitive to assumptions regarding the composition or configuration of the nebula.

The purpose of this paper is to examine the possible boundary conditions for the state of primordial gas in a solar nebula, and of solids condensing out of such a gas. The discussion will be based on the evidence

from meteorites and on the currently most popular, although not necessarily realistic, type of models for solar nebulae.

SUMMARY OF COSMOCHEMICAL INFERENCES

The present status of our information from meteorite research bearing on the early states of the solar system together with some aspects of interpretation have been summarized in recent reviews, most comprehensively by Anders (1971, 1972 a, b). The main import of the interpretative part of this work is that the condensation of solids took place from a neutral gas of "cosmic" composition during its cooling from temperatures of the order of 2000 °K down to temperatures of the order of 200 °K. The solid condensate is suggested to have the same temperature as the ambient gas at all times. This assumption is of fundamental importance in discussing the chemical aspects of the condensation process; it implies that this process can be described in terms of chemical and thermodynamic equilibria between phases which are at the same temperature.

The inferred gas pressures are in the range of 10^{-6} to 10^{-3} atmospheres. Neither the time span of condensation nor the cooling mechanism for the gas are specified. However, some exemplary results are presented where the cooling time in one case is taken to be of the order of minutes to hours (where the solids would condense practically without interdiffusion) and in another case, of the order of years to centuries (with complete diffusional equilibration, permitting the formation of solid solutions to the limit of solubility).

PREMISES OF INFERENCE

In trying to examine the conclusions drawn with regard to the temperatures of gas and solids, we find that the inference that these have the same temperature is an aesthetically determined choice without physical or chemical basis. It is thus really not an inference, but a postulate. It depicts a situation which can be easily materialized in a wide range of temperatures in terrestrial laboratories, but which can be achieved only under very special circumstances in space.

Furthermore the inference that the gas is cooling at the same rate as the grains during the process of condensation appears not to be independently considered. A scrutiny of the literature reviewed by Anders indicates that this is also an *ad hoc* assumption introduced to satisfy the "equal temperature" assumption. The fact that the cooling processes of a gas in space and those of a solid, and hence their cooling rates, are not identical, does not appear to be taken into account.

THERMAL EQUILIBRIUM

For the sake of discussion we shall here accept the conceptual nebular models, Fig. 1, invoked in most current chemical discussions. We shall for the moment ignore their other inconsistent features. For a discussion of these see Alfvén and Arrhenius (1973) and Arrhenius (1972) and references therein.

We shall use the state of thermal equilibrium between the gas and solid grains as a basis for discussing the conditions for condensation and evaporation. We employ the term, thermal equilibrium, in a special sense here. The gas-grain system as a whole is not in thermodynamic equilibrium; it continues to lose energy as long as T_g is greater than T_r , as discussed under the heading, Cooling of Gas. Any grain is in thermal equilibrium in the sense that its rates of heat loss and heat gain are balanced. This state of thermal equilibrium does not necessarily imply a temperature equilibrium. Let us recognize that when we speak of temperatures of gas and solids in space, especially in the case of a solar nebula, we are dealing with three different temperatures, which may be defined as follows:

1. A *kinetic temperature* T_k may be assigned to a body of gas in space if the particles in the gas have achieved Maxwellian velocity distribution.
2. A solid (or liquid) body in space has a temperature T_b , which to a fair approximation may be called a *blackbody temperature*. When this solid body is immersed in the above gas, T_k and T_b are usually not identical.
3. A star radiates like a blackbody (with superimposed emission and absorption lines) because the photons emitted by the excited and ionized gases assume an equilibrium distribution, viz., Planck distribution. The space in the vicinity of a star has a *blackbody radiation field* due to the stellar radiation. This field may be locally characterized by a *blackbody temperature* T_r .

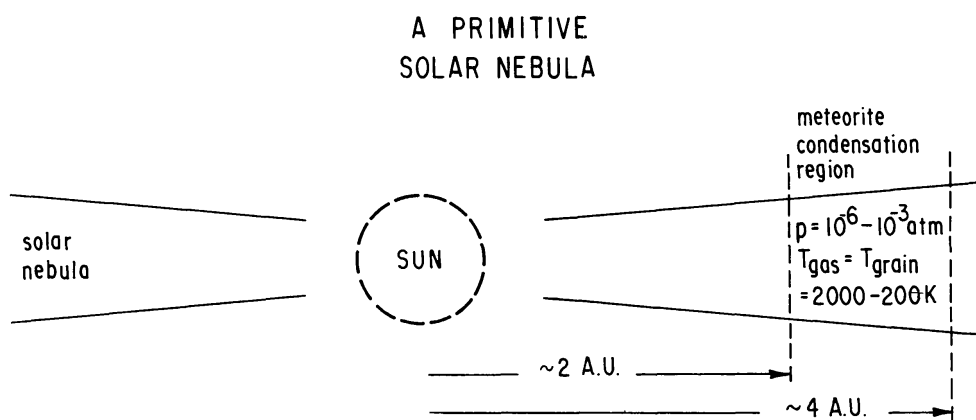


Fig. 1. A conceptual sketch of the primitive solar nebula adopted (solely for the sake of discussion) in this paper, and indicating the region in which the meteoritic source material is supposed to have condensed. The commonly postulated physical conditions in this region during condensation are also indicated.

The equilibrium temperature T_b of a solid body in the vicinity of a star and immersed in a gas of temperature T_k is, among other parameters, a function of T_k and T_r . The temperature T_b is given by the condition that the rate of heat loss by the solid body equals its rate of heat gain.

If the gas is in the composition range loosely referred to as “cosmic” then we may fairly assume that it consists predominantly of hydrogen. Let us assume that a grain immersed in hydrogen gas at temperature T_k and subjected to solar radiation at the present rate has an equilibrium blackbody temperature T_g . At the site of the grain the solar radiation field has a temperature T_r . Let N be the density of the gas and V be the effective velocity with which the molecules impinge on the grain surface. Suppose for the sake of simplicity that the grain is spherical and rotating. Then the amount of heat that the grain receives from the radiation field is

$$G_1 = \sigma T_r^4 \text{ ergs cm}^{-2} \text{ sec}^{-1} \quad (1)$$

where σ is the Stefan-Boltzmann constant. The amount of heat that the grain receives from the gas is

$$G_2 = C N V \frac{3}{2} k (T_k - T_g) \text{ ergs cm}^{-2} \text{ sec}^{-1} \quad (2)$$

where C is a constant representing the efficiency with which an impinging molecule transfers its energy to the grain surface. The velocity V is given by

$$V = \left(\frac{kT_k}{2\pi m} \right)^{1/2} \quad (3)$$

m being the mass of the molecule. The heat lost by radiation from the grain, assumed to be a blackbody, is

$$L = \sigma T_g^4 \text{ ergs cm}^{-2} \text{ sec}^{-1} \quad (4)$$

The condition for thermal equilibrium is now given by

$$G_1 + G_2 = L \quad (5)$$

The value of the constant C is likely to be much less than 1 in an actual situation. However, we shall put $C = 1$ in our calculations and understand that the grain temperatures that we thus obtain are an upper limit. Equation 5 holds in a region where the radiation from neighboring grains does not constitute a significant heat source for the grain in question, *i.e.*, in a region from which the infrared radiation emitted by the grains can escape freely. The need for this assumption in any region where condensation takes place is evident from the Section, Cooling of Gas.

Notice in equation 5 that one possible solution is $T_g = T_r = T_k$. All other solutions must have all three temperatures unequal. The former situation prevails if we put a quantity of gas at some initial temperature inside a solid “black” enclosure and put this enclosure in empty space. After some time both the enclosure and the gas will then be found to have the same temperature as the local radiation field. The important difference between this example and the case of a solar nebula at incipient condensation is that in the latter case there is nothing that serves the role of the walls of the enclosure. If solid grains are present in significant amounts, they play this role and tend to bring the gas temperature down to T_r , their own temperature also approaching T_r at the same time. This process will be discussed in a later section.

Figure 2 shows the grain temperatures as a function of the gas temperature calculated from equation 5 for two different regions: the terrestrial region where we have assumed $T_r = 300^\circ\text{K}$ and the asteroidal region (sometimes assumed as a source region for meteorites) where we have assumed $T_r = 100^\circ\text{K}$. The range of gas densities are chosen so as to cover approximately the pressure range of 10^{-6} to 10^{-3} atmospheres. Note that the equilibrium grain temperatures are several hundreds of degrees to over a thousand degrees lower than the gas temperature in the range shown. For the very high grain temperatures, in the range of 1800°K , commonly assumed for the most refractory phases, the gas temperature exceeds $10,000^\circ\text{K}$ on the lower gas density curves. Note also that these grain temperatures represent an upper limit. The realistic grain temperatures are likely to be somewhat lower depending on the value of C . There will not be any significant change of the gas-grain temperature differential demonstrated here if we take into account the departure of the grain material from a perfect blackbody.

However, even for materials with perfect blackbody behavior, a departure from the Planck’s law of radiation occurs when the size of the grains is very small. Such grains cannot absorb or emit radiation of wavelengths larger than their own dimension very efficiently. If we assume that the absorption and the emission efficiency of these small grains is $\frac{a}{\lambda}$, where λ is the wavelength of radiation and a is the grain radius, then the corrected grain temperature T_{ga} is easily shown to be given by

$$T_{ga} \approx T_g \left[\frac{C}{3 a T_g} \frac{T_k - T_{ga}}{T_k - T_g} \right]^{1/5} \quad (6)$$

where T_g is the grain temperature as given by Fig. 2. A realistic value of the constant C is of the order of 0.1. With this value and with $T_g = 1000^\circ\text{K}$, $T_k = 2000^\circ\text{K}$ and $a = 0.1 \mu\text{m}$, this relation gives $T_{ga} \approx 1200^\circ\text{K}$ with $a = 0.01 \mu\text{m}$

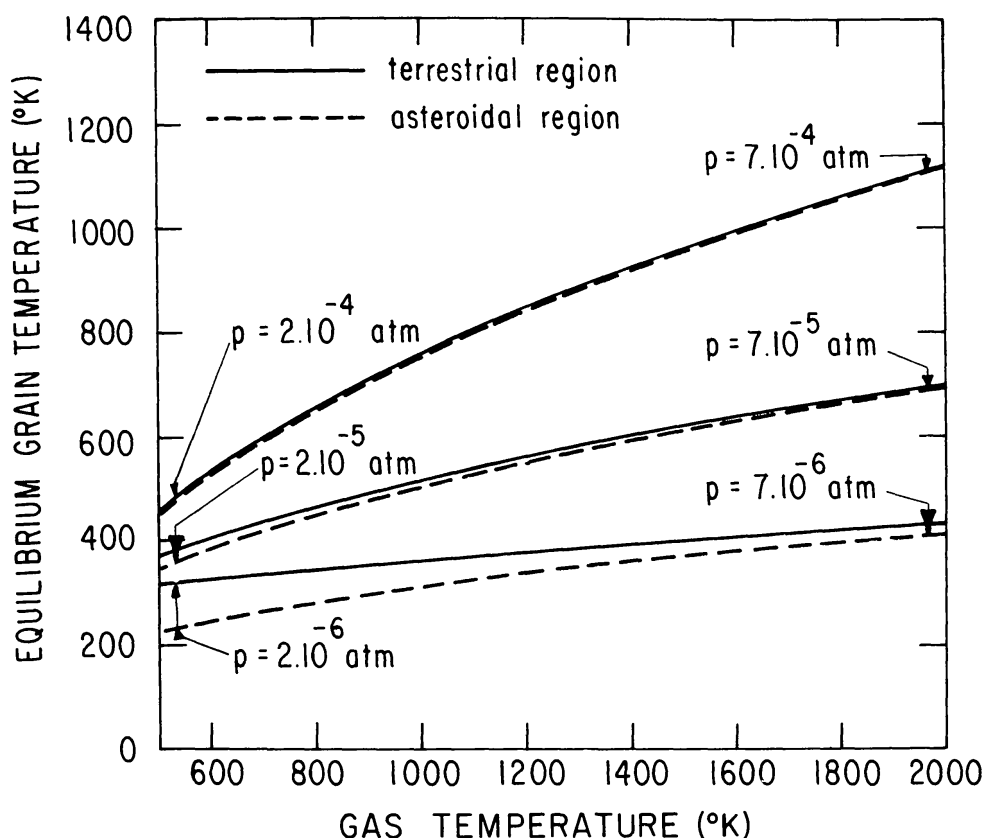


Fig. 2. Temperatures of grains in thermal equilibrium with gas and radiation field. Such equilibrium would in the models discussed here pertain in the entire nebula in the incipient stages of condensation. It would persist in regions where condensation could, by definition, continue, regardless of developing grain opacity.

In the terrestrial region the radiation temperature has been taken to be 300°K and in the asteroidal, 100°K . Each pair of curves corresponds to a fixed gas density and hence the gas pressure varies along these curves. Note that the equilibrium grain temperatures given here are an upper limit and the actual temperatures are likely to be lower.

The pressure range shown is within the one commonly assumed in "instant nebula" type models. In these the total amount of planetary matter with a complement of hydrogen and helium are assumed at one given time all to be distributed in the disc formed by the rotating solar nebula. The difficulties encountered in such models are discussed in the references given in the Section, Thermal Equilibrium.

instead, we get $T_{ga} \approx 1600^{\circ}\text{K}$. Hence our conclusion regarding a substantial gas-grain temperature differential remains unchanged. This effect, which is important for grains with radii of the order of $0.01\ \mu\text{m}$, will not be discussed any further in this paper.

Another source of heat for the grains is the association of hydrogen atoms in the grain surfaces. Calculations that include this effect show that this does not significantly change the temperature differential between the grains and the gas under the conditions visualized in the nebula.

A detailed analysis of thermal equilibrium of solid grains in contact with gas and radiation field and the criteria for condensation or evaporation, have been given by Lehnert (1970). Lehnert's analysis takes into account the heat as well as the material balance terms that arise due to condensation or evaporation of the partially ionized gas. Such effects have been purposely, but unrealistically, ignored in the present discussion in order to keep it in the same framework as that of the concepts under discussion here.

An examination of equation 5 would at once show that it is possible to make T_k and T_g arbitrarily close by making the gas density N very high, although T_k and T_g may never be exactly equal. In the temperature range 2000 °K, this would require pressures of the order of 10 atmospheres or higher.

APPROACH TO EQUILIBRIUM OF AN INITIALLY HOT GRAIN

Suppose next that due to some instantaneous process the grain is raised to a temperature close to that of the gas and much higher than T_g . It may then be suggested that this grain would approach its low equilibrium temperature so slowly that the entire condensation process may be thought to take place while the grain is still almost as hot as the gas. To explore this possibility let

- N_c = Number density of condensing molecules
- V_c = Effective velocity of flow of condensing molecules to the grain surface
- m_c = Mass of condensing molecules
- m_g = Mass of the growing grain (instantaneous)
- a = Radius of the growing grain (instantaneous)
- a_0 = Radius of the grain at time $t = 0$
- ρ = Density of grain material
- s = Specific heat of grain material

Then an upper limit to the rate of grain growth is given by

$$\frac{da}{dt} = \frac{N_c m_c V_c}{\rho} \quad (7)$$

and

$$a(t) = a_0 + \left(\frac{da}{dt}\right)t \quad (8)$$

where we have assumed that N_c is not changing rapidly with time. The rate of heat loss by the grain is given by

$$\frac{d}{dt} (m_g s T_g) = 4\pi a^2 \left[\frac{3}{2} N V k (T_k - T_g) + \sigma (T_r^4 - T_g^4) \right] \tag{9}$$

Hence the rate of cooling of the grain is

$$\frac{dT_g}{dt} = \frac{3}{s \rho a(t)} \left[-s \rho T_g \left(\frac{da}{dt} \right) + \frac{3}{2} N V k (T_k - T_g) + \sigma (T_r^4 - T_g^4) \right] \tag{10}$$

Figure 3 shows the cooling of an iron grain (with $T_r = 300^\circ\text{K}$ and $T_k = 2000^\circ\text{K}$) for various initial grain radii. We find that the time to cool to the

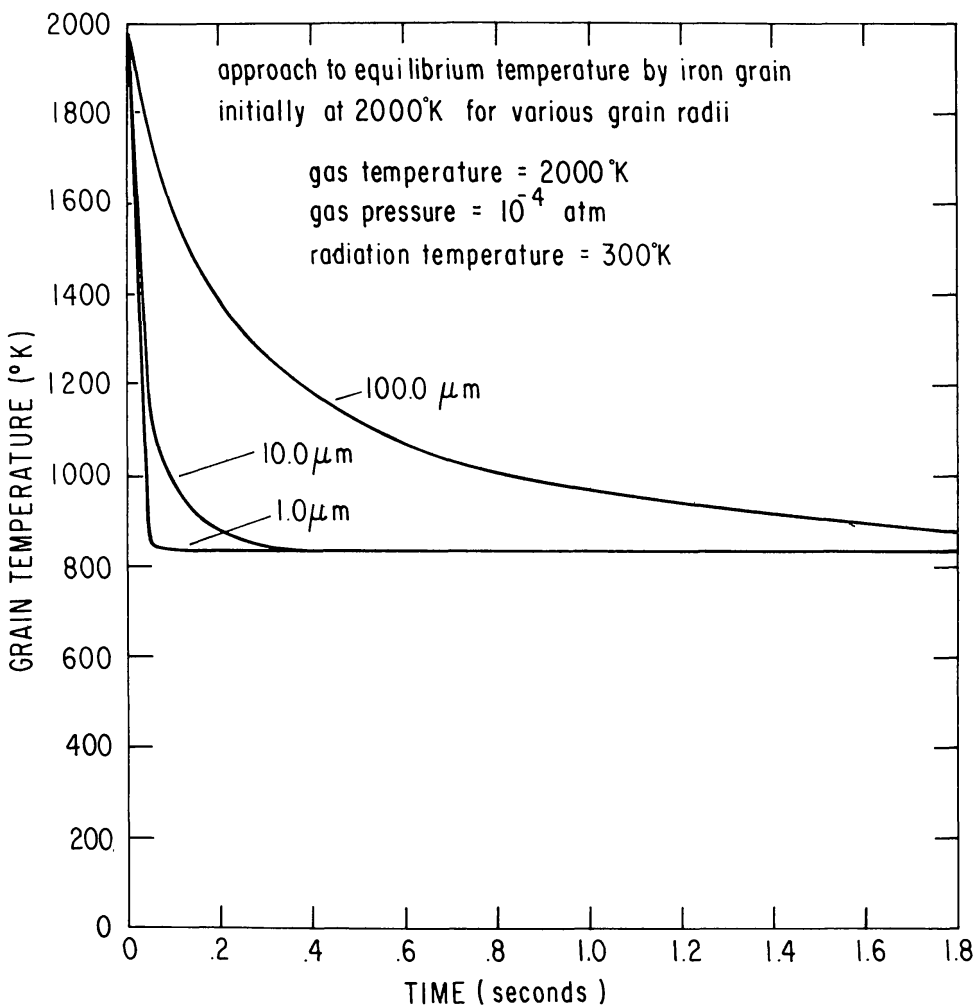


Fig. 3. Cooling to equilibrium temperature of an iron grain which has been raised to a high temperature (here 2000°K) by some transient process. The numbers alongside the curves indicate the grain radii at time $t = 0$.

equilibrium temperature is of the order of seconds. The conclusion obviously is that if due to some instantaneous process the temperature of a grain is raised, it will very quickly relax back to its equilibrium temperature.

The case where a large number of grains are present simultaneously is discussed in the Section, the Greenhouse Effect.

COOLING OF GAS

Let us next turn our attention to the physical conditions in a nebular gas which consists predominantly of hydrogen, and, to begin with, without any condensed particles. The abundance of molecular hydrogen in this gas is somewhat uncertain since photodissociation of H_2 molecules has to be taken into account. An upper limit to the abundance of H_2 is given by assuming only collisional dissociation. The dissociation energy of H_2 molecules is about 4.5 eV and hence at any temperature T the number of molecules having energies in excess of the dissociation energy is

$$N_d = 2N (\pi k^3 T^3)^{-1/2} \int_{4.5}^{\infty} \exp(-\frac{E}{kT}) E^{1/2} dE \quad (11)$$

With a gas density of $N = 10^{15} \text{ cm}^{-3}$ and a gas temperature $T = 2000^\circ \text{K}$, *i.e.*, a gas pressure of the order of 10^{-3} atm , N_d is about 10^7 cm^{-3} . With $T = 1000^\circ \text{K}$, N_d is about 10^{-3} cm^{-3} .

In reality, the H_2 molecules may also suffer photodissociation. However, under the conditions envisioned, very few dissociating photons can reach the region 2-4 A.U. from the sun without being absorbed in the intervening medium. Furthermore, if solid grains are present, they provide an efficient means of association (Brecher and Arrhenius, 1971). Hence although the degree of dissociation may be higher than indicated above, the conclusion would still be valid that molecular hydrogen would predominate in the gas temperature range 200 to 2000°K in the type of models considered. In these it is generally assumed that adiabatic heating of a contracting nebula brought the temperature to the level assumed at the onset of condensation. The only available source of energy to the gas during condensation would be the solar luminosity. This energy source is inefficient in communicating heat energy to the molecular hydrogen gas (see, *e.g.*, Kahn and Dyson, 1965).

The predominant source of radiative energy loss would be the excitation and deexcitation of the rotational levels of H_2 molecules. However, with the gas densities as indicated above, the radiation will be self-absorbed in the nebula even if the smallest dimension of the nebula is of the order of one solar radius. Cooling will then be confined to the edges of the nebula initially, and the region of cooling will expand inward with time.

A similar conclusion also applies to possible radiative cooling due to other molecules such as CO.

The purpose of the above discussion is merely to show that in the models discussed, it has yet to be shown how the gas alone can cool from 2000 °K to 200 °K in times of the order of minutes to centuries. This discussion is however, academic when we note that there is another very efficient cooling mechanism, which may dominate all other mechanisms, *viz.*, the cooling due to the radiation from the grains in contact with the gas. The grains being at a temperature higher than the local radiation field, radiate energy faster than they absorb from the radiation field. The excess energy comes from the kinetic energy of the gas molecules impinging on the grains. This energy loss far exceeds the radiative loss or the energy gain from the solar radiation by the gas. Consequently, the gas continues to cool and so do the grains, but each at a different rate. If N_g is the number density of the grains, then the rate of cooling of the gas is given by

$$\frac{d}{dt} \left(\frac{3}{2} N k T_k \right) = -4 \pi a^2 N_g \sigma (T_g^4 - T_r^4) \quad (12)$$

where T_g is a function of T_k as given by equation 5 and a is given by equation 8. Note again that due to the assumption $C = 1$, the cooling rates obtained here would represent an upper limit. As will be pointed out in the Section, The Greenhouse Effect, cooling due to this process also will be initially confined to the edges of the nebula and will gradually proceed inward, with the major condensation always taking place in the region of cooling.

In Fig. 4 we have computed the cooling rates for various values of N_g . We find that the cooling times would typically be of the order of days. Hence the gas and the solid in the surface region of a nebula of this kind would cool rapidly, each one at its own rate and with T_g always at values intermediate between T_k and T_r .

Thus, if the solar nebula had the properties ascribed to it, the condensation would be catastrophically rapid with the condensing grains always at a lower temperature than the gas until T_r is reached. The primordial condensate would consist of a quenched, undifferentiated smoke. This conclusion was drawn on similar premises by Urey (1952).

Since then, extensive investigations of meteorites have been carried out suggesting a primordial condensate instead largely consisting of well crystallized, differentiated solids, representing a sequence of crystallization temperatures. Hence it has become necessary, also for this reason, to replace nebular concepts of the kind mentioned above with models that satisfy the requirements of the chemical observations and also the requirements of energy conservation.

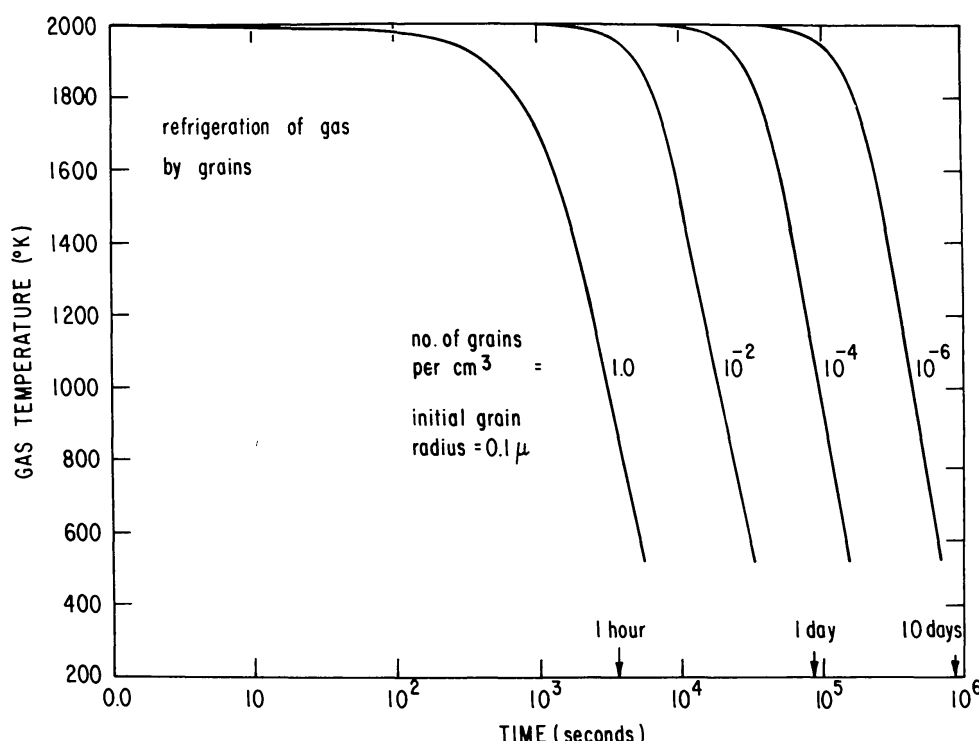


Fig. 4. Cooling of gas due to refrigeration by the grains. The curves are calculated for various grain number densities. The cooling times shown here are a lower limit. If the equilibrium value of the grain temperatures (Fig. 2) is lower, the cooling times would be longer.

THE GREENHOUSE EFFECT

The grain temperatures that we have obtained in the Section, Thermal Equilibrium, were calculated under the assumption that the infrared (IR) radiation emitted by the grains can escape freely from the region of the grains, *i.e.*, the IR opacity in the gas-grain cloud is negligible. It is often suggested, however, that the cloud would, for some reason, be opaque to IR radiation, so that the radiation field in the deep interior of the cloud would be modified due to the capture of IR photons. This would mean that another term, G_3 , would have to be added to the left-hand side of equation 5, to represent this additional heat source.

An IR opacity may be produced either by IR-absorbing gas components or by grains. First we shall assume that the opacity is produced by the grains alone. Let us, for the sake of simplicity, visualize the gas-grain cloud as a disc of half-thickness Z , as sketched in Fig. 1. Suppose that the gas has a uniform temperature of 2000°K throughout the cloud, and that the pressure is 5×10^{-4} atm, so that in the absence of any greenhouse effect the grain temperature would be about 1000°K , according to equation 5. Let T_g be the grain temperature at any point in the cloud, and T_{gc} and T_{ge} be its values at

the midplane and at the edge (surface) of the cloud, respectively. If τ is the optical depth for grains situated at a depth z from the edge, then we can write $\tau = \pi a^2 N_g z$. From the elementary theory of radiative transfer in plane parallel layers we then have

$$T_g^4(\tau) = T_{ge}^4 \left[1 + \frac{3}{2} \tau \right]. \quad (13)$$

However, this relation holds only when there is a thermodynamic equilibrium between the grains and the radiation field, *i.e.*, when the temperature of the radiation field equals the grain temperature. Clearly, this is not true at the edge of the cloud, but this would be true in the interior if the opacity due to the grains is large. In order to take this effect into account, let us make the following simplifying but reasonable assumption: At points interior to $\tau = 1$, the radiation field is in equilibrium with the grains. At all points between the edge and $\tau = 1$, the grain temperature is T_{ge} , as would be given by equation 5, *i.e.*, in the present case $T_{ge} = 1000^\circ\text{K}$. The temperature of the radiation field between the edge and $\tau = 1$ can be estimated roughly by making the simple approximation that the mean intensity of radiation declines as $\exp(-\tau')$, where τ' is measured outward from $\tau = 1$. Hence, the temperature of the radiation field declines as $\exp(-\tau'/4)$, leveling off to the value T_r at a large distance.

In order to achieve a temperature equilibrium between the grains and the gas in the central regions of the cloud, we require $T_{gc} = 2000^\circ\text{K}$. From equation 13 and the above assumptions, this requires that the optical depth to the midplane be $\tau_c = \pi a^2 N_g Z = 11$. With grains of radius $1\ \mu\text{m}$, this means that we must have about 10^9 grains per cm^2 in a column normal to the disc. If, as is often done, we visualize the condensation region as a ring around the sun 3 A.U. in radius, and of rectangular cross section 0.1 A.U. on the side, then the above requirement is equivalent to the existence of about $10^{24} \rho\ \text{gm}$ of $1\text{-}\mu\text{m}$ grains. This is the order of magnitude of the total mass in the asteroids. The implication of this order-of-magnitude estimate is that a major fraction of the total available mass must have already condensed in order to produce the desired greenhouse effect. The early condensates would thus form in a transparent cloud under the conditions of a pronounced gas-grain temperature differential persisting throughout the cloud.

We will, however, for the sake of argument, assume conditions of extreme screening to have somehow prevailed even in the early part of the condensation period, and also assume that all of the micron-sized grains have somehow succeeded to remain in suspension. Under these conditions a temperature distribution such as described above would be established. In Fig. 5 we have plotted the temperatures of the gas, the grains, and the radiation field, as functions of the optical depth. Note that at the edge of the cloud the temperature of the radiation field is of the order of 800°K , and

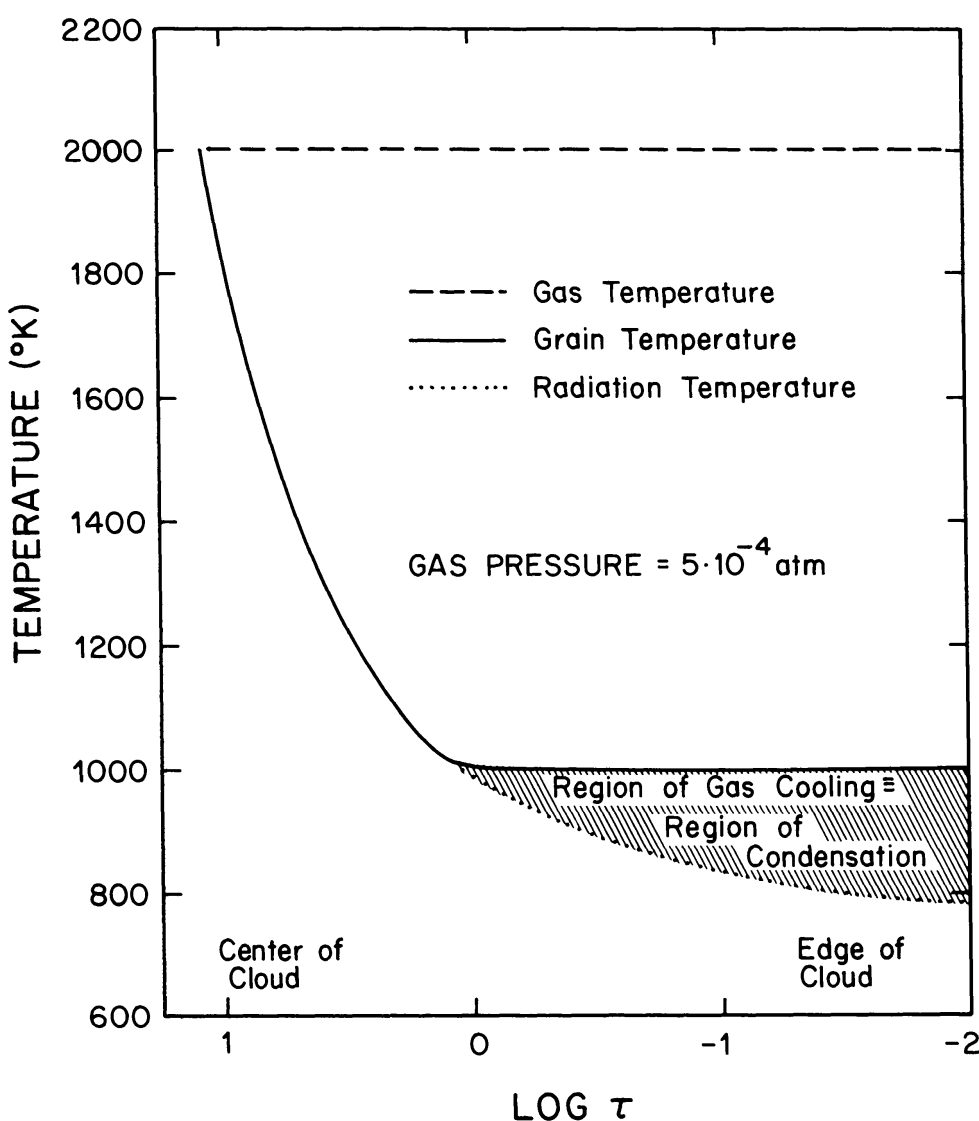


Fig. 5. Temperatures of gas, grains and radiation field as a function of optical depth in a disc-shaped cloud around the sun as sketched in Fig. 1. Equality between the gas and the grain temperatures is achieved at the midplane of the disc if the optical depth to the midplane is 11. Cooling of the gas, whether radiative or via the grains, then takes place at the edges of the cloud which by definition constitutes the region of condensation.

not the solar radiation temperature, $T_r = 100^\circ\text{K}$, that we used to calculate T_{ge} . However, this makes very little difference, since the value of T_{ge} is about 1060°K if we use $T_r = 800^\circ\text{K}$ instead.

Turning our attention to the opacity due to the gas, we note that the most dominating IR-absorbing molecule would be H_2O , whose abundance relative to H_2 molecules in the type of models discussed would be $\leq 10^{-3}$. The opacity due to this contribution would vary irregularly with the grain

temperature but would always be considerably less than the large grain opacities discussed above.

REGION OF CONDENSATION

For the condensation of solids, a cooling of the gas is essential. If this cooling is due to radiative processes, then it must be confined to the edges of the cloud where the optical depth for the escape of photons is small. However, it is more likely that the predominant cooling is due to the grains themselves, as discussed in the Section, Cooling of Gas. Note from equation 12 that this cooling requires that T_g and T_r be different. This is true only at the edges of the cloud. In absence of a substantial energy source for the nebula, as is the case here, the region of cooling will gradually expand inward and so will the region of condensation with its pronounced gas-grain temperature differential.

Thus, regardless of the cooling mechanism and the opacity assumed, cooling, and hence condensation are confined to the regions of the cloud where a pronounced gas-grain temperature differential always exists.

PROPERTIES OF PRIMORDIAL GRAINS

With regard to the interpretation of the meteoritic observations, several important conclusions follow from the temperature differential $T_k - T_g$:

1. The grain temperatures in actual thermal equilibrium are lower by several 10^2 degrees than those calculated for the case of temperature equilibrium. The gas temperatures are characteristically larger by a factor of 10.

2. The high gas temperatures lead to distributions in the gas of chemical and isotopic species which differ substantially from what would be the case in the situation of temperature equilibrium.

3. The sequence of condensation in space, with a large difference between the gas and the grain temperatures, is similar but not identical to that in a system of gas and grains cooling together at the same temperature and at the same rate in an opaque enclosure such as a furnace. The difference in the chemical speciation in the gas would, among other factors, be expected to lead to "anomalies" in the sequence, such as observed in the meteorites. Such effects would be most noticeable in the early condensates, formed at very high gas temperatures of the order of 10^4 °K, and also in the lower range of the condensation sequence. The former include incorporation of volatile elements such as the halogens, mercury, indium and noble gases in association with "high temperature minerals" and the growth from the vapor phase of "highly refractory" calcium silicate whisker crystals subsequent to the crystallization of less refractory magnesium silicates (Fuchs, 1971). On the basis of careful considerations the reverse would be expected (Grossman, 1972) if condensation took place in temperature equilibrium.

In the range of low grain temperatures, the associated high gas temperatures make it possible to understand the formation by direct vapor growth of ferrosilicates, ferroferrispinel and ferrigarnet – the former two being abundant in meteorites. To understand their growth at grain temperatures where an assumed coexisting isothermal gas would be incapable of providing a source, it has been suggested that metallic nickel iron provided a source material by becoming oxidized and subsequently reacting with magnesium and calcium silicates in the solid state. The latter is counterindicated by the fact that no such diffusion couples are observed in meteorites, and that such diffusion reactions are exceedingly slow even at temperatures much higher than those postulated. The suggestion that iron oxide (Fe_3O_4 , ferroferrispinel, magnetite) in meteorites would have formed by oxidation of nickel iron metal grains is shown to be highly unlikely by the fact that the oxide crystals lack the metal characteristically precipitated as microscopic metallic inclusions in the course of such oxidation (Boström and Fredriksson, 1966; Kerridge, 1970).

CONCLUDING REMARKS

The treatment of condensation in space as an isothermal gas-grain phenomenon has the fictitious advantage of simplifying the problem by reducing the number of variables. This advantage is offset by the fact that the problem, in the manner shown, becomes removed from the realm of reality.

Nonetheless calculations based on temperature equilibrium are useful as long as they are considered strictly as gross initial approximations. The advantage of such a first step lies in the fact that it makes use of the existing large body of empirical chemical equilibrium data, which is only partially or indirectly applicable to the real situation. In the cases where the results of such calculations agree with observations in meteorites and in laboratory experiments one can conclude that the observed parameters are insensitive to the variables studied within certain limits.

In those more interesting cases where deviations are found between the inapplicable theory on one hand and observation on the other, valuable clues can be obtained with regard to parameters such as the temperature differential between solid and gas, and the states of dissociation, excitation and ionization of the various gas components. In situations where condensation nuclei were absent, supersaturation phenomena could be important (Blander and Katz, 1967). Such situations would, however, presumably be rare in view of the ubiquitous occurrence of dust in the universe, particularly in a circumstellar region of accumulating matter.

Before the effects of these many variables can be separately and quantitatively specified, extensive laboratory experiments under controlled conditions are necessary (Meyer, 1969, 1971; Arrhenius and Alfvén, 1971; Brecher and Marti, 1972; Brecher, 1972). To gain control of some of the

important parameters, studies under wall-free and weightless conditions are desirable; opportunities for this important class of experiment will hopefully be offered in Earth-orbiting facilities. Indeed, the quantitative laboratory study of these largely unexplored but profoundly important relationships constitutes a new field of experimental petrology applicable to space, which will hopefully attract the skill and imagination of the pioneers in lunar and meteorite research.

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